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14. ABSTRACT

During the Anthro-Centric Multisensory Interface for Sensory Augmentation of Tele-Surgery (ACMI-SATS) project, the research team developed a testbed that allows for testing and evaluation of hypotheses related to tele-surgical robotic human-centered surgeon interfaces, cognitive workload, efficiency and situation awareness. The ACMI-SATS testbed includes both physical surgical robotic capability and simulation environments to maximize the efficiency of system development. ACMI-SATS provides a human centered multisensory interface that allows one or more surgeons to collaborate one or more cases simultaneously, whether co-located or remotely distributed. We completed the testbed hardware and software and developed a set of ACMI-SATS augmentations for testing during out-year funding and future studies focused on development of optimal tele-surgical, tele-mentoring and remote operations technologies and methodologies for both military and civilian applications.

15. SUBJECT TERMS

Tele-surgery, human machine interface, sensory substitution, tactile interfaces, cognitive workload, surround sound, 3D display

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Introduction

Robotic tele-surgery is a promising application of robotics to medicine, aiming to enhance the dexterity and sensation of minimally invasive surgery through use of millimeter-scale robotic manipulators under the control of a surgeon. Current interfaces prevent surgeons from exploiting sensory capabilities, leading to underutilization of many potential capacities offered by robotic tele-surgery. To advance the state of the art in the field of human-machine interface (HMI) design for tele-robotic surgery, the Florida Institute for Human and Machine Cognition (IHMC) executed the Anthro-Centric Multisensory Interface for Sensory Augmentation of Tele-Surgery (ACMI-SATS) project for the U. S. Army Telemedicine and Advanced Technology Research Center (TATRC). ACMI-SATS developed methods to improve tele-surgery effectiveness in military and civilian applications by improving the sensory and control interface using HMI principles to increase efficiency and reduce surgeon cognitive workload and errors.

Background

Tele-operated surgical (tele-surgical) endoscopic robotic systems have rapidly become the standard of practice for many surgical procedures. This technology reduces surgical trauma to the patient, lowers postoperative complications, improves surgeon ergonomics, reduces effects of surgeon motion tremors and enables the performance of novel techniques (e.g., the end effector can perform actions that a human appendage cannot, such as locking in position or rotating past anatomical limits). These "surgery by wire" systems can remove the need to transport the patient or place the surgeon in harm's way to provide definitive surgical care and have the potential to proactively prevent undesirable actions, automate repetitive tasks and enable safer training through simulation. Hirshauer (1991), however, notes that endoscopy separates the eye from the hand of the surgeon, preventing perception of the useful kinesthetic feedback from direct interaction with the tissues present in traditional "open" procedures, and the reliance on video displays creates a visual information flow bottleneck. This increases the visual workload and can lead to increased surgical errors, longer intraoperative sessions (with accompanying increased anesthesia risks) and decreased number of procedures performed in a given time period. Technological systems that utilize visually dominant displays, such as those used in virtual environment (VE) simulation and training, have shown improved user task performance when combining both tactile and visual sensory information (Briggs & Srinivisan, 2001; He & Agah, 2001). Virtual reality (VR) training systems have been developed to bring VE simulation to surgical training (Satava, 1995; Gallagher et al., 2005), however, VEs that lack realistic kinesthetic and haptic feedback show increased errors (Cohn et al., 2000). Combining visual, spatial audio and tactile sensory modalities, can improve performance and situation awareness (SA) in complex dynamic tasks (Raj, Kass & Perry, 2000; Diamond et al., 2003; Olson et al., 2004; Erikson et al., 2008; Fuchs et al., 2008; Merlo, Gilson & Hancock, 2008).

Telerobotic systems such as the da Vinci® Si HD (Intuitive Surgical, Sunnyvale, CA) must employ torque, position, velocity and strain sensors to maintain accurate closed-loop, servomotion. Beyond control loop error based force-feedback, however, presentation of these data streams in raw form would not provide the requisite sensory data needed to enhance the surgeon's experience. The addition of high definition (HD) stereoscopic visual displays can provide sufficient cues to create a visual perception of haptic feedback (Hagen et al., 2008). A sensory experience limited to vision, however, still lacks the richness and subtleties available during open surgery and decrements procedural consistency, workload and operative efficiency (Tavakoli, Patel & Moallem, 2005; Zhou et al., 2008). Moreover, these systems require that the surgeon remain seated, with his or her head down at a control console to perceive the three dimensional video and use the fixed hand controllers. While this compares favorably to standing astride an operating table using laparoscopic instruments, the most favorable ergonomics would facilitate free movement, posture and position to reduce fatigue and potentially allow the surgeon to perform more procedures in a given time.

In the military medicine domain, tele-surgical systems have the potential to revolutionize combat casualty care by bringing definitive surgical trauma care to the wounded servicemember without placing surgical specialists in harm's way. Current technology developments such as the United States Department of Defense (DoD) Defense Advanced Research Projects Agency (DARPA) Trauma Pod (Figure 1) seek to further reduce the time needed for delivery of surgical intervention by installing a complete tele-surgical system into robotic vehicles (Burnett, 2007; Satava, 2005a, 2005b). These Trauma Pods could be remotely driven to wounded soldiers in the field, providing an opportunity to treat severe wounds within the "golden hour" following injury (Pueschel, 2006). Deploying a fleet of such vehicles to a theater of operations would provide maximum benefits by providing the potential for immediate care to multiple wounded servicemembers with polytraumatic injuries following, for example, a detonation of an improvised explosive device (IED). In such a scenario, if a small team of surgical specialists (e.g., orthopedic, cardiovascular, neuro, general/trauma surgeons, etc.) could easily and safely handoff control of the robotic system between each other as needed, they could potentially stabilize and provide definitive care to the maximum number of casualties. Because there would be no cross contamination between patients (or need to scrub or change sterile garments), the trauma team could manage the surgical needs of multiple patients more effectively. Experience with other robotic systems, such as unmanned aerial vehicle (UAVs), however, has shown that the addition of robotic technology to a given mission can actually adversely increase manpower requirements (Franke, et al., 2005).

Figure 1: DARPA Trauma Pod Concept (lead by SRI International) loading a wounded servicemember (left), evaluating the trauma (center) and performing surgery (right). Images downloaded from: http://www.technovelgy.com/ct/Science-Fiction-News.asp?NewsNum=364, and http://brl.ee.washington.edu/Research_Active/Surgery/Project_09/Project_09.html

The addition of HD stereoscopic visual displays to robotic surgery systems provides an initial step toward improved sensory interface design. However, lack of haptic feedback in endoscopy can lead to surgical errors such as tearing of tissues, broken sutures and hemorrhage, especially in delicate or intricate procedures (Bethea et al., 2004; Vassiliades, 2006). One approach to enhancing haptic feedback embeds tactile force reflection transducers on the fingertips in the surgeon console hand controllers (Figure 2) to provide a reflection of the force applied by endoscopic graspers capabilities (Morimoto et al., 1997; Bar-Cohen et al., 2001; Tavakoli, Patel, & Moallam, 2005; Culjat et al., 2008). While this technique has demonstrated improved surgical technique (reduced grasping force), the surgeon's auditory and tactile sensory capabilities remain underutilized while his or her visual sense remains highly task loaded. Alternate haptic interfaces that provide end effector force feedback indicate proportional resistance to commanded movements and complement the visual display to reduce workload (Wagner, Stylopulos, Jackson & Howe, 2007). However, the narrow field of view provided by the endoscope negatively impacts situation awareness (SA) by limiting perception of complex spatial relationships within the body cavity. This loss of SA may lead to inadvertent incursion into sensitive structures following camera orientation changes or movement of internal organs. These haptic approaches borrow concepts from the VE and VR worlds that place a high premium on *presence* (the convincing sense of perceiving as if physically in the VR or VE). In

contrast, tele-surgery must place the highest premium on effective *treatment* of the patient by optimizing perception of patient state to the surgeon. Because the feedback generated by the sensors in the operative field is no longer directly coupled to the surgeon's hands (either through direct contact with the tissues or indirect contact via rigid laparoscopic instruments), opportunities now exist to utilize other sensory substrates. In fact, some actions in surgical robotic manipulation can cause the surgeon to make inadvertent hand movements due to haptic force feedback errors (Tavakoli, Patel, & Moallem, 2005). Unlike classic VE/VR approaches to haptics in tele-surgery, these alternative display technologies could complement or supplant traditional haptics without affecting or interfering with the motion of the primary control input mechanism. For this discussion, we define haptics as telepresence related kinesthetic sensory interactions and tactile as general or abstract tactual interactions.

Figure 2: (left) Electro-rheological fluid (ERF) based haptic surgeon hand interface (Bar-Cohen et al., 2001); (center) Force transducer fitted to endoscopic grasper; (right) Pneumatic haptic finger tip display (Culjat et al., 2008) integrated with da Vinci® hand controllers.

Because perception takes place in the brain, not at the end organ (Bach-y-Rita, 1972), the brain can learn to reinterpret the meaning of signals from specific nerves (e.g., from tactile receptors) given appropriate self-generated feedback (Buonomano & Merzenich, 1998). This forms the basis for interfaces that can non-invasively and unobtrusively use alternative sensory pathways to provide information. This means that the information displayed does not necessarily need to represent the underlying data at high resolution, rather abstract representations of the sensory environment information can provide sufficient data for operator decision making and improved SA (Raj, Kass & Perry, 2000). Such sensory substitution mechanisms have been demonstrated in tele-surgical applications (Kitagawa et al., 2005) and exploit the plasticity inherent to the brain and nervous system, which supports both long-term and short-term anatomical and functional remapping of sensory data (Finkel, 1990; Walcott & Langdon, 2001). Therefore, a new class of interfaces could be incorporated into the tele-surgical surgeon interface. Tactile and spatial audio displays that provide higher-level representations of data could provide metadata or information that a surgeon could not physically sense directly, even during an open procedure.

Divorcing the surgeon's sensory perception from direct mechanical linkage to the patient, the operative field, and the surgical instruments could also enable a paradigm shift in tele-surgical methods. Laparoscopic instruments were initially developed as extended versions of their counterparts used in open procedures (e.g., extended length scissors, needle drivers, etc.); even though the scaling induced poor ergonomics, familiarity with the older tools existed. Likewise, current tele-surgery systems utilize tools that mimic the laparoscopic instruments, replacing the direct mechanical connection with an electronic one. The functional capabilities (e.g., degrees of freedom) of the robot end effectors (such as the da Vinci® EndoWrist®) exceed those of laparoscopic instruments and human hands. Advances in head mounted displays (HMDs) and motion capture from the commercial sector have advanced sufficiently to allow both freedom of movement and high-resolution stereoscopic visual perception without confining the user to a fixed console. Motion capture could translate movements that match the scale and trajectories of normal (real-world) kinesthetic interactions, as well as enable the use of motion

gestures to accomplish supervisory-controlled actions to take advantage of the capabilities of modern robotic surgical systems. Because kinesthetic perception includes both self-perception (proprioception) and perception of changes in the environment (Hannford & Venema, 1995), proprioceptive sensations could disambiguate abstract sensory substitution displays of end effector motion. The full use of arm movements (versus hands only) could provide more accurate mapping to the degrees of freedom available in modern surgical robots.

Clearly, adding additional sensory channels would increase the volume of information flow to the surgeon. The human brain, however, has developed to make use of multi-sensory inputs in the natural world, which provides a richer sensory environment than most man-made systems. This increase in information transduction will also markedly increase the bandwidth requirements for data flow between the robot (e.g., installed in a Trauma Pod) and the remote surgeon (Hannford & Venema, 1995). Recent DoD projects such as the High Altitude Platforms Mobile Robotic Tele-surgery (HAPsMRT) (Broderick, 2006; Rosen & Hannaford, 2006) and the Smart Codec with Tele-surgery Capability (Energid Technologies, Cambridge, MA), respectively, have developed methods that use unmanned aerial vehicles to reduce the radio frequency signal lag between the surgeon and the robotic end effectors and to develop efficient algorithms for data transmission (Figure 3).
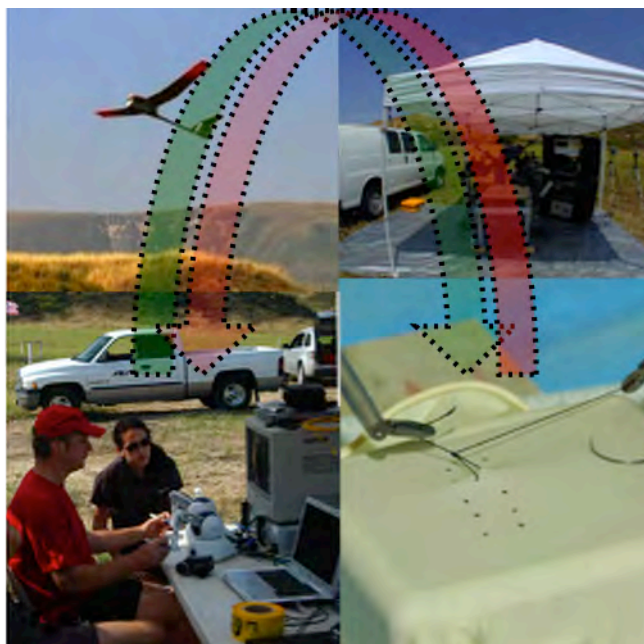
F**igure 3:** High Altitude Platforms Mobile Robotic Tele-surgery (HAPsMRT) technology demonstration using real time data compression and UAV relay for haptic tele-surgery interactions (Broderick, 2006). A UAV (left, upper) relays surgeon movements (left, lower) to a surgical robot (right, upper). Haptic hand controllers provide feedback for suture task (right, lower).

When processing and interpreting tactile data, specific traits of human sensation and cognitive processing (such as adaptation, habituation, or satiation to durative stimuli) may interfere with perception of persistent tactile and other sensory stimuli. Adaptation occurs when a signal persists for an extended period of time (e.g., the tactile sensation of wearing a watch is automatically filtered out by the peripheral and central nervous system). Habituation occurs when a durative signal repeats periodically (e.g., a ticking clock) and is no longer perceived. Satiation, also the product of prolonged stimulation, produces specific spatial distortions (Cholewiak, 1976), perhaps based on transient plasticity (Whitsel et al., 1989; Merzenich, Recanzone, Jenkins, Allard & Nudo, 1988). These are issues with known solutions currently implemented in IHMC's Adaptive Multiagent Integration (AMI) software (e.g., modulation of waveform characteristics of persistent cues) that mitigates their effects. AMI agents can also generate sensory illusions, such as spatial audio, the saltation rabbit illusion (Geldard & Sherrick, 1972, Geldard, 1975; Bremer, Pittenger, Warren, & Jenkins, 1977) and spatial summation (Craig, 1968). Recent studies have confirmed that tactile illusions are processed at the cortical level as if they were real; that is, no differences between illusory and veridical tactile stimulation patterns manifest in functional magnetic resonance (fMRI) scans of the human brain (Blankenburg, Ruff, Deichmann, Rees & Driver, 2006). Therefore, tactile illusions could improve perception of tactile signals beyond the display's physical resolution.

Prior research by this team and others on tactile sensory substitution has shown that the brain is capable of integrating the information from an artificial receptor, arriving via a brain-machine interface (BMI), in a perceptual experience that depends upon the nature of the information gathered by the specific artificial receptor (Bach-y-Rita, 1972, 1995; Bach-y-Rita, Collins, Saunders, White & Scadden, 1969). The BrainPort® device (Wicab, Inc., Madison, WI) provides information to the brain through electrotactile stimulation of the tongue (Bach-y-Rita, Kaczmarek, Tyler, & Garcia-Lara, 1998). Receptors on the tongue surface are uniquely qualified to receive electrical impulses because of the density and sensitivity of nerve fibers at this site, the electrolyte (saliva) that allows it to receive and maintain electrical contacts and its proximity to the brainstem, minimizing perceptual lag. With the highest resolution device currently available, an approximately 25x25 tactile image (some are not active) is created by a sequence of pulses presented at a rate of 200 Hz. The amplitude value (voltage) of the pulse sequence or 'burst', updated at 50 Hz, varies with the grayscale level of a video image. The participant controls the overall intensity (voltage) level, which does not exceed 15VDC. The second novel electrotactile interface, the VideoTact, which is placed on the abdomen and worn discretely under the user's clothing, exploits the larger surface area of the abdomen to provide a larger display area. While the density of torso sensory receptors is lower than the tongue, placing a high-resolution display (i.e., 24x32) on the abdomen allows for rapid perception of object motion (Bach-y-Rita et al., 1969). An electrolyte gel ensures electrical contact with the skin.

Figure 4: Non-visual interfaces utilized in ACMI-SATS: (left) BrainPort® Intraoral Device electrotactile tongue array (600 tactile pixels). (center left) VideoTact (ForeThought Development, LLC, Blue Mounds, WI) electrotactile abdominal display (768 tactile pixels). (center right) Tactile Situation Awareness System (TSAS) implementation with 24 vibrotactile transducers in a tactile torso interface (TTI). (right) 10.2 speaker surround sound system.

A number of recent and ongoing studies with the have shown that blind individuals can recognize elements of standard eye charts (Sampaio, Maris & Bach-y-Rita, 2001, Kupers, Sampaio, Moesgaard, Gjedde & Ptito, 2003) and labyrinthine defective individuals (those with inner ear balance disturbances) can dramatically improve balance (Tyler, Danilov & Bach-y-Rita, 2003) by using the BrainPort®.This requires that the user have control of the movements of the sensor in order to self-generate feedback to reinforce the novel sensory stimuli. In the absence of the sensory-motor loop, we have observed that the sensory stimulation through a tactile array is perceived as a purely tactile experience localized to the body part in contact with the array. Laboratory studies and operational test and evaluation of the Tactile Situation Awareness System (TSAS) and other tactile displays have shown that individuals rapidly localize and respond to encoded tactile cues presented on the torso and limbs (Calhoun, Draper, Ruff & Fontejon, 2002; Diamond, Kass, Andrasik, Raj & Rupert, 2003; Raj, Kass, & Perry, 2000; Sarter, 2001; McGrath, Estrada, Braithwaite, Raj & Rupert, 2004). This forms the rationale for utilizing self-generated natural movements of the hands, arms and body to control robotic systems. The current IHMC TSAS implementation uses a vest with 24 tactors in a tactile torso interface (TTI) that can operate effectively with the VideoTact and the BrainPort® devices.

Natural motion gesture-based control reduces the workload and learning associated with standard joystick/button input devices, and providing low latency feedback through haptic

interfaces allows precise control of an external system with minimal training time. Blinded servicemembers learned to stabilize and manipulate the tactile image with their prosthetic eyes within 10-20 minutes, demonstrating that the tactile feedback does not need to be presented through the hands for accurate perception and control of a dynamic action. During this 22-month project, we evaluated performance of specific tasks using the Mimic training simulator and the Zeus, using gestural commands with tactile and auditory augmentation of large screen visual displays. In this project, we have used gesture recognition agents in AMI, based on a finite state machine (FSM) approach to recognize gestural requests to lock robot joints during specific tasks, such as selecting the robot arm, switching between simultaneous procedures, and handing-off control between the surgeon and first assistant. We have demonstrated that one user can switch at will between two surgical procedures and that two participants can share control of the same robot, using head tracking and natural movement gestures as an efficient method of hand-off or procedure switching.

Figure 5: Body position (inset) tracked with ShapeWrap system using IHMC's AMI architecture. Box projected under avatar indicates stable platform for a given stance.

Obtaining high gesture recognition accuracy requires the ability to accurately sense the position and configuration of a user's hands, limbs, head and torso. IHMC has developed custom software implemented in AMI that allows rapid, accurate detection (within a few millimeters) of relative positions of body components, estimation of center of gravity, ground reaction force, center of pressure and estimation of dynamic stability. This system incorporates data from a custom built wireless, wearable force sensing insole system with 132 load cells per foot (Pressure Profile Systems, Los Angeles, CA) and a full body/limb/head wireless, wearable motion capture system (ShapeWrapIII, Measurand, Inc, Fredericton, NB) that has been integrated into the ACMI-SATS prototype to provide the user with sense of proprioception and interaction with the ground through the haptic interfaces (Figure 5).

Figure 6: (left) Gesture based controller for robotic arm simulator. (right) *Status post* binocular enucleation, a servicemember uses his prosthetic eyes to control a tracking reticle on the screen with tactile (tongue based) display of area displayed inside the reticle (near user's finger).

In addition to the loss of qualitative haptic and tactile sensation rising from the transition from open to endoscopic procedures, the surgeon also loses the significant kinesthetic feedback associated with somatic movement. Through motion scaling in robotic systems (unlike laparoscopic systems) surgical robots can translate gross arm, torso and head movement gestures into precise movement of surgical instruments. These large movements can provide a kinesthetically rich experience for the user, who can move freely and with natural motion. Previously, IHMC and its research partners demonstrated gestural control of fine movements of a robotic arm simulator and stabilization of visual imagery represented tactually to recently blinded servicemembers. In the former application, the operator controls the National Aeronautics and Space Administration (NASA) Basic Operational Robotics Instruction System (BORIS) software robot (Gilliland et al., 2005) with natural arm and hand movements. In the latter, the BrainPort® tactually presented image provides "gaze" movement cues to the user to dynamically position his extraocular muscle controlled prosthetic (glass) eyes (Figure 6).

Project Activities

While awaiting delivery of our da Vinci® S HD simulator (dV-Trainer, Mimic Technologies, Inc., Redmond, WA), we initiated development of a simulation environment for IHMC's existing Zeus surgical robot hardware (Computer Motion, Goleta, CA), and assembled a simulation area in our laboratory space. We acquired two additional Aesop arms that are functionally equivalent to Zeus arms (aside from the micro wrist) to implement a four-arm solution (Figure 7) similar to the da Vinci® system for testing hardware modifications prior to implementation on the Zeus.
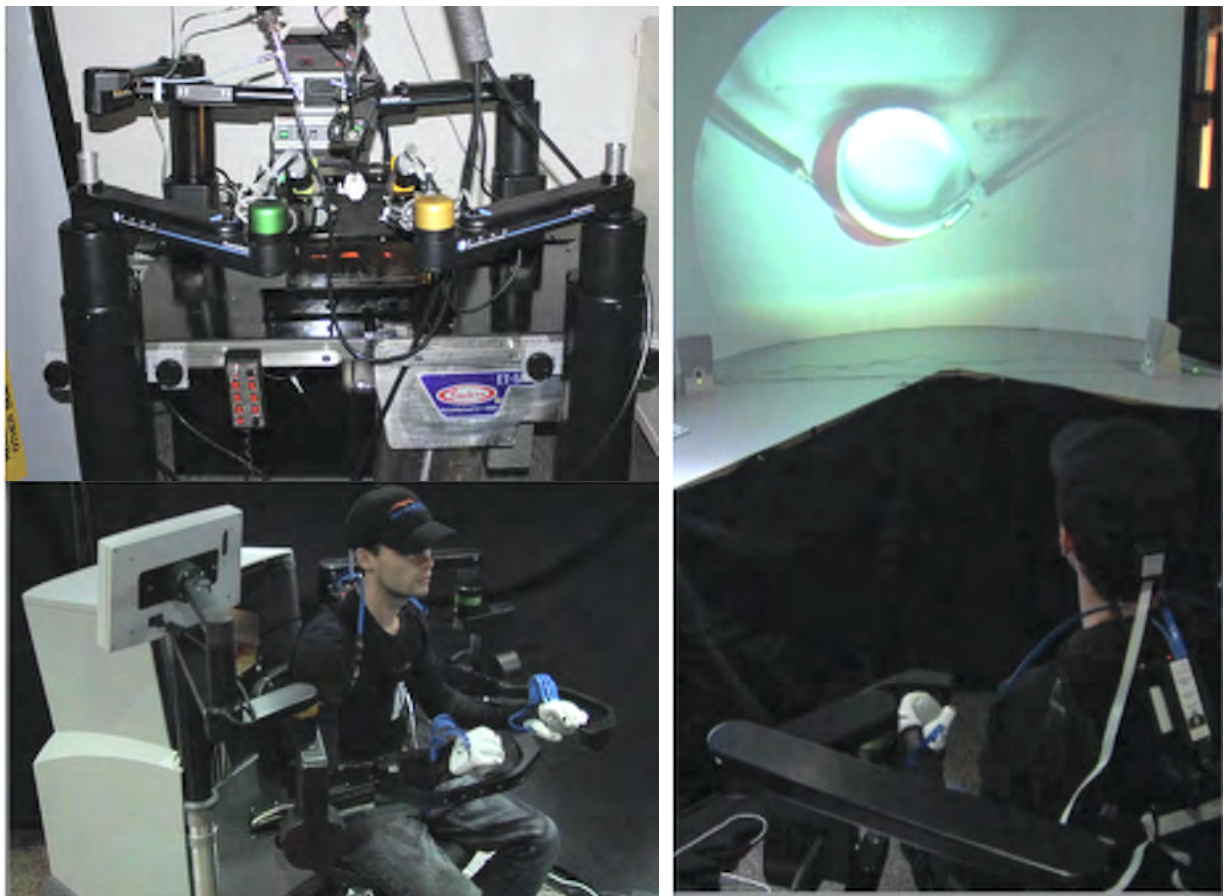
Figure 7: (left, top) IHMC ACMI-SATS Zeus configuration with four robot arms. In the center of the operating table, a plexiglass "patient simulator" provides a closed environment for endoscopic activities. (left, lower) The Zeus can be controlled by the stock control input devices, or with more natural movements using motion capture. (right) Human scale projected imagery from the Zeus testbed.

In parallel with circuit mapping of the Zeus controllers to extract position and force sate variables from the Zeus actuators, we developed a virtual prototype of the Zeus robot in order to test hypotheses without the constraints of interaction with physical hardware. We implemented the virtual robot in the Java programming language using Simulation Construction Set (SCS) from Yobotics, Inc (Cincinati, OH). The simulator created an accessible environment that allows for rapid evaluation and testing of tele-surgery augmentation concepts. The simulation (Figure 7) provides a physics-based, kinematically accurate graphical simulation of the robot arms and allows for development, test and evaluation of ACMI-SATS concepts prior to testing on the hardware. The Yobotics SCS allows both simulated input and real world sensor inputs to drive the motion of the arms. Input signals and robot responses can be displayed in strip chart form and recorded. These recordings can then be played back at various speeds relative to real-time to fully explore response characteristics.

Using AMI, we integrated our wireless full-body, wearable motion capture system (ShapeWrapIII) with our Yobotics simulation of the four-arm Zeus. We updated 1970's era pen-plotter routines for "look ahead" operations that use the system model to smooth motion despite varying time steps and noise. This algorithm "chops" the command signal at a high frequency and sends these small time-step data packets serially to the actuators. The simulation injects a variable delay and noise to the signal. At the actuator end, a model of the system with the known sample rate helps determine signal delays and extrapolate the likely trajectory when delays occur. This feature would be useful for remote tele-surgical applications that suffer from intermittent communications or low bandwidth (e.g., TraumaPod).
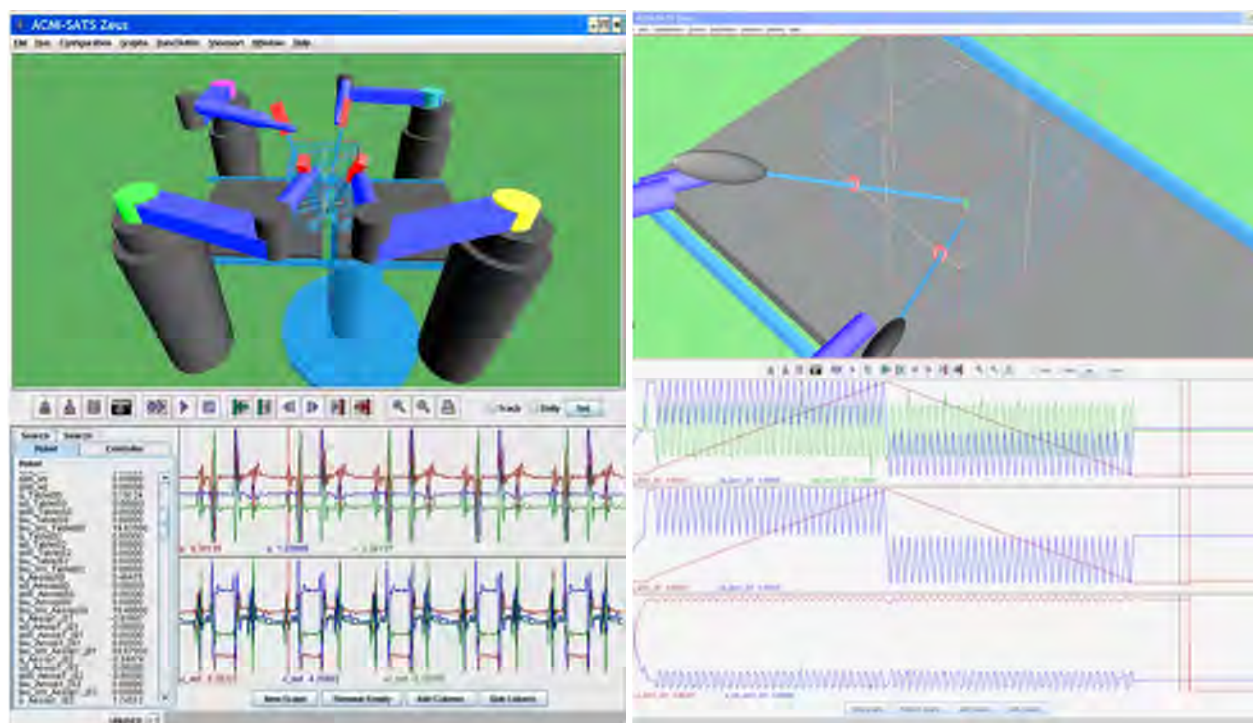
Figure 8: (left) Yobotics Simulation Construction Set implementation of IHMC's current Zeus-based ACMI-SATS surgical robot configuration. Top frame shows graphical model of configuration shown in Figure 1. Left panel provides a list of joints in the system and their orientations, torques, rates, etc. Lower panel shows strip chart representation of variables selected from the list in the left inset panel. (right, upper panel) Simplified physics only model of two robotic arms with port reaction forces modeled. (right, lower panel) Velocity command trajectory (red) of one arm "chopped" at high frequency (blue) with added (simulated) noise and variable delay (green) are shown in the top plot. The middle plot shows the arm trajectory (red) reconstructed piecewise from the high frequency data segments.

Figure 8 (right) shows an intermittent command signal (blue) being smoothed in to a smooth velocity using the look-ahead algorithm (New Scientist, 1972). A musical instrument digital interface (MIDI) control surface (BCF2000, Behringer International GmbH, Willich, Germany) allows for manual positioning of simulation parameters (such as friction, rates and joint positions). This mechanism allows offset adjustment to match body movements to robot actions.

We modified the actual Zeus hardware to connect to a computer via USB using analog to digital converters (ADCs) and digital to analog converters (DACs) to allow direct control of the robot arms and monitoring of both position and current draw via AMI (USB-AI16-16A and USB-AIO16-16A, respectively, Acces I/O Products, Inc., San Diego, CA). With this connection, we can utilize auditory and tactile interfaces for representation of Zeus data using the AMI software agents developed with the Yobotics simulation. Using these agents, we developed a number of electrotactile symbologies for representation of the positions and forces on the end effectors as well as relative locations and forces on the robot arm shafts. The end effector information displays on the tongue using the BrainPort® device and shaft data displays on the abdomen via the VideoTact electrotactile interface. Both the BrainPort® and the VideoTact devices, as well as a 10.2 channel surround sound system, were evaluated as potential sensory augmentation methods for surgical interfaces. We transitioned these methods to the Mimic dv-Trainer to include direct control of the Mimic dV-Trainer actuator positions, orientations and graspers. By presenting the visual imagery from the endoscope or the simulation onto a large screen (via projection of large screen LCD), ACMI-SATS maps the apparent size and movement of the end effectors to an approximate 1:1 ratio with the user's arm and hand movements (Figure 9).

Figure 9: Mimic dV-Trainer imagery projected a reasonable approximation of the size of the human hand and arm. Motion capture of hand and arm movements maps 1:1 to onscreen robot movement. This allows for veridical kinesthetic and proprioceptive cues to augment visual information. Screen on left shows graphical representation of electrotactile stimulus on the tongue that represents closure angle (distance between tactile icons) and forces (intensity of stimulus) on the two (right and left) grasper end effectors.

With the ShapeWrapIII, the ACMI-SATS system can accurately track arm, torso and head position. We use this data to track the relative position and orientations of the wrists to drive the position and orientation of the Zeus Microwrist or Mimic EndoWrist® and operate the graspers

(opening and closing the hand opens and closes the grasper proportionally; making a scissors cutting motion with the index and middle finger actuates the scissor end effector; extending the index finger alone drives blunt dissection with a closed grasper). This allows the user to utilize kinesthetic feedback to improve SA. We also added head tracking (OptiTrack, NaturalPoint,Inc., Corvalis, OR) to the control input stream to automatically change the point of view camera location with user head movement. This camera control mechanism provides motion parallax tied to the user's x, y and z axis head movements to create a dynamic viewpoint that supports intuitive user interaction. As the user moves toward and away, left and right, or up and down, with respect to the screen, the camera system zooms in and out or shifts the view in the simulation appropriately to create an effective three dimensional (3D) viewing experience. Because drastic movements would affect system performance, and surgical tasks typically require lower dynamics, simple velocity cut-offs prevent unintentional motions from changing the view or moving the robot. This allows the surgeon, for example, to rapidly reposition his or her hands without actively clutching while also preventing a sneeze from causing a robotic mishap. While this model-based approach is trivial to implement with simulators (e.g., Yobotics and Mimic dV-Trainer), we can accomplish the same effect with actual video streams by integrating a real-time 3D model creation capability.
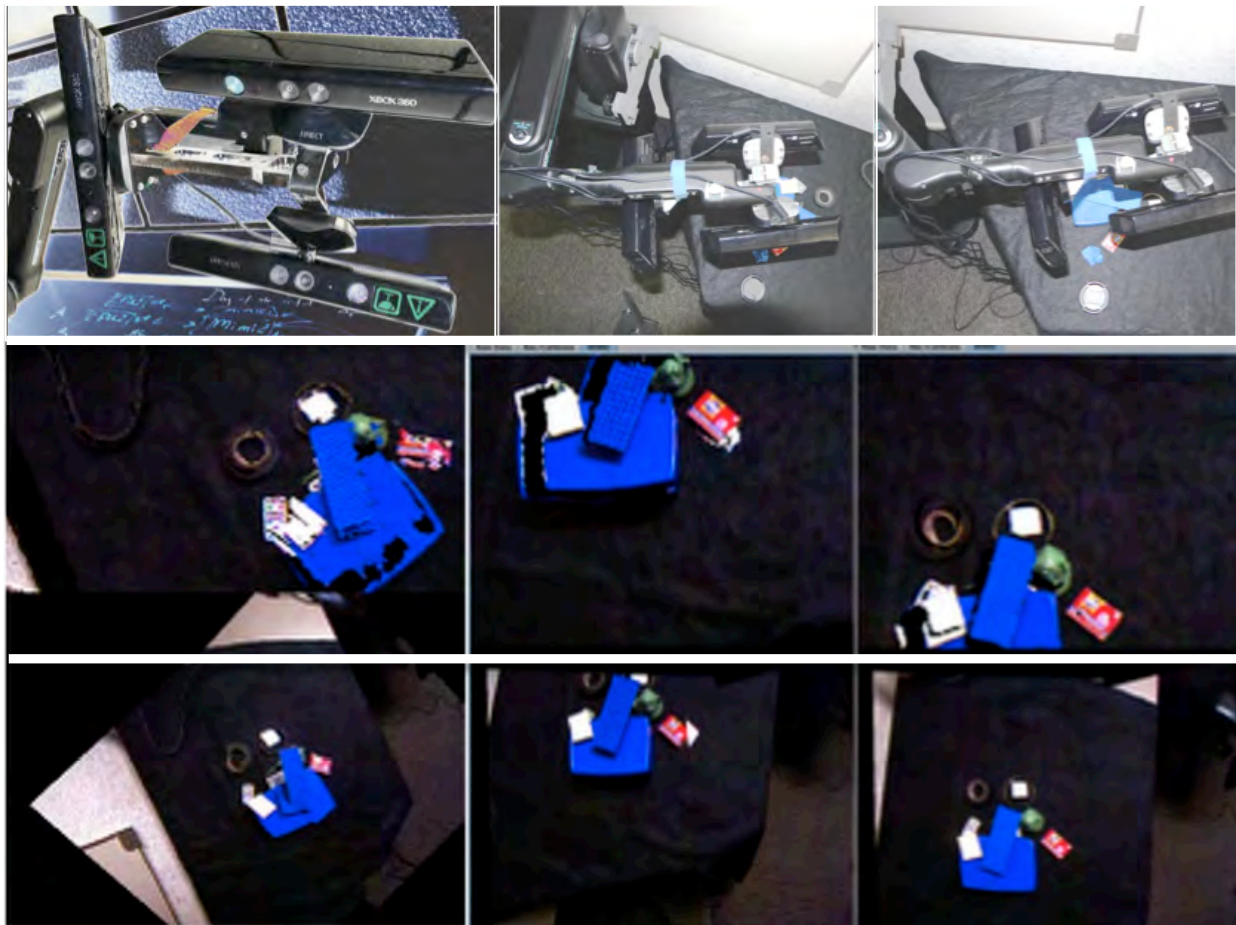
Figure 10: (top row, left to right) Imaging camera system (3 Kinect™ cameras) mounted to endoscope positioner robot (Aesop 3000, Computer Motion, Inc., Goleta, CA) as seen from below; Positioner and camera's retracted (center) and extended (right) as seen from above, over table with colored objects. (middle row) 3D model reconstructed from bottom row composite camera and range sensor data (bottom row) showing (left) digital zoom and rotation of image and model (cameras stationary); (center) model and composite image with Kinect™ array positioner retracted and (right) with positioner extended.

We initially investigated the possibility of using structured light (Tardif & Roy, 2005) to create models through the endoscope, however, during this project, the Kinect™ camera and depth sensor system (Microsoft, Corp., Redmond, WA) became available. This sensor provides, at low cost, the data needed to generate 3-D models of the environment under study. Using three cameras and a custom simultaneous localization and mapping algorithm (SLAM) implemented in AMI, we can provide parallax cues and maintain SA regarding the location of objects that now fall outside the endoscope field of view (Figure 10). In this implementation, the camera array moves in proportion with slow head movements such that the visual scene matches live camera images. For head movements that have velocities or trajectories that exceed the limitations of the camera actuator, the visual image rotates and translates. This allows for the imagery dynamics to match the user's head movements without lag imposed by mechanical endoscope movement and provides depth cues for 3D perception without requiring the surgeon to don special goggles or sit at a stereoscopic display console. It also provides a point of view that moves in an intuitive fashion with the head, such that moving forward or backward increases or decreases the zoom level, respectively. Vertical and horizontal motion causes appropriate movement of the point of view in the simulation and the parallax to provide a convincing sense of depth (Figure 11). This provides a more natural perception of depth than the current, fixed stereoscopic video image approach, which lacks parallax. The camera can be locked (using a hand gesture) in a given viewpoint or moved continuously with the head (which provides a visual sensation similar to that of an open surgical procedure and removes the need to toggle between endoscope and arm controls). Gestural movements of the fingers allow for selection of mode (e.g., lock position, clutch, activate electrocautery, etc.) and arm (e.g., arm two or three) without using foot-activated switches.
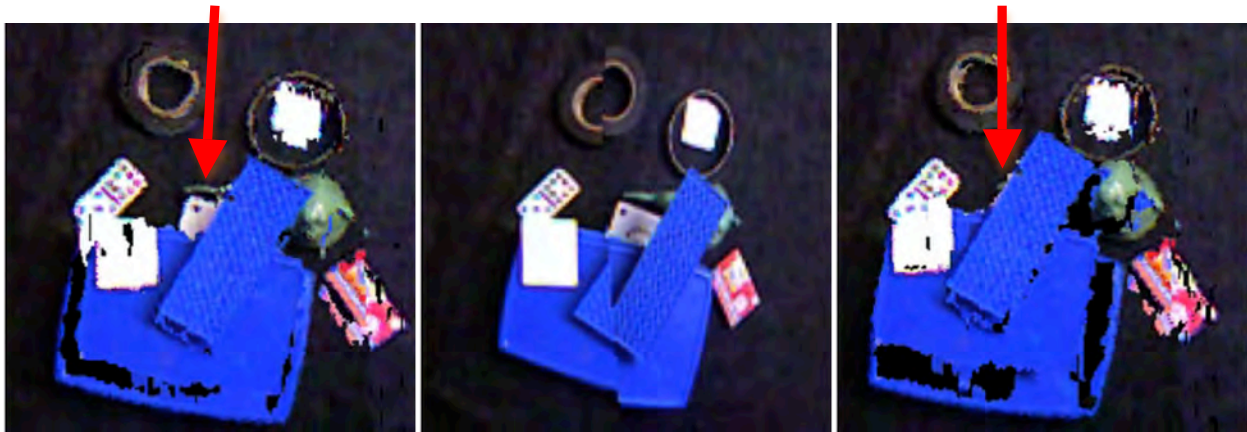
Figure 11: Parallax cues emerge in the 3D model generated from the composite image (center) generated by the camera array (not used by the surgeon) after normalizing for angle. Movement of the users head to the left (left) exposes the playing card (arrow) and covers the green cone partially. Moving to the right (right) causes the nearer blue rectangle to obscure the card and fully expose the green cone.

Multisensory Implementations

By using the AMI framework, we have been able to couple a wireless, wearable motion capture system, the surgical robot environment and appropriate sensory feedback displays to improve the user experience. In addition to the visual improvements described above, we have fully implemented a set of tactile and auditory cueing capabilities in ACMI-SATS to allow evaluation of task performance with research participants under future funding vehicles. A connection between the AMI system and the Zeus or the da Vinci® simulation system allowed for interactive simulation and testing of the full ACMI-SATS concept. Mimic Technologies, Inc., provided appropriate software hooks and documentation to enable AMI to interface to simulation variables including setting and reading the states of the endoscope and both the shafts and

graspers of the EndoWrists®. In addition we can retrieve the applied forces, (i.e., pushing and pulling forces) on tissues as well as grasping forces. Figure 12 shows a flow chart of one particular ACMI-SATS onfigura-tion detailed in the following sections.

Kinesthetics: Gestural movements of the fingers for selection of mode (e.g., lock position, clutch, activate electrocautery, etc.), arm (e.g., arm two or three) and head allows the user to simultaneously change viewpoint and maneuver the robot end effectors. The motion parallax provides a convincing sense of depth in the 2D image. With the imagery scaled up to present the end effectors as approximately the same size as the users hands (when seated or standing near the center of the room), kinesthetic feedback provides additional intuitive cues. This exemplar tracks hand and digit position data from the Measurand AMI software agent, with the GestureGraspAgent computing the distance between the fingers of interest (thumbs and indexes of each hand).
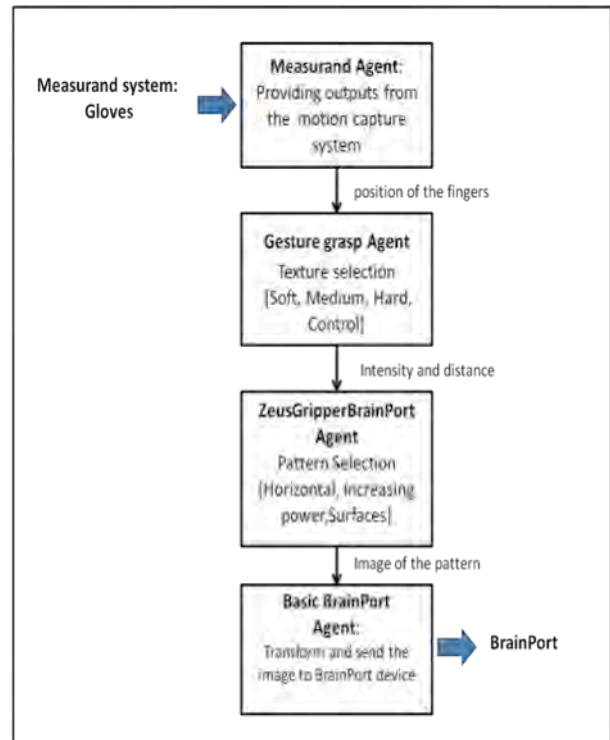
Figure 12: Flow chart of a full ACMI-SATS imple-mentation for the Zeus surgical robot (see text).

Tactile Feedback: The GestureGraspAgent sends the current distance between the fingers and the current intensity value to the ZeusGripperBrainPortAgent. The agent uses the values to create an image of the pattern of stimulation sent to the BrainPortAgent.
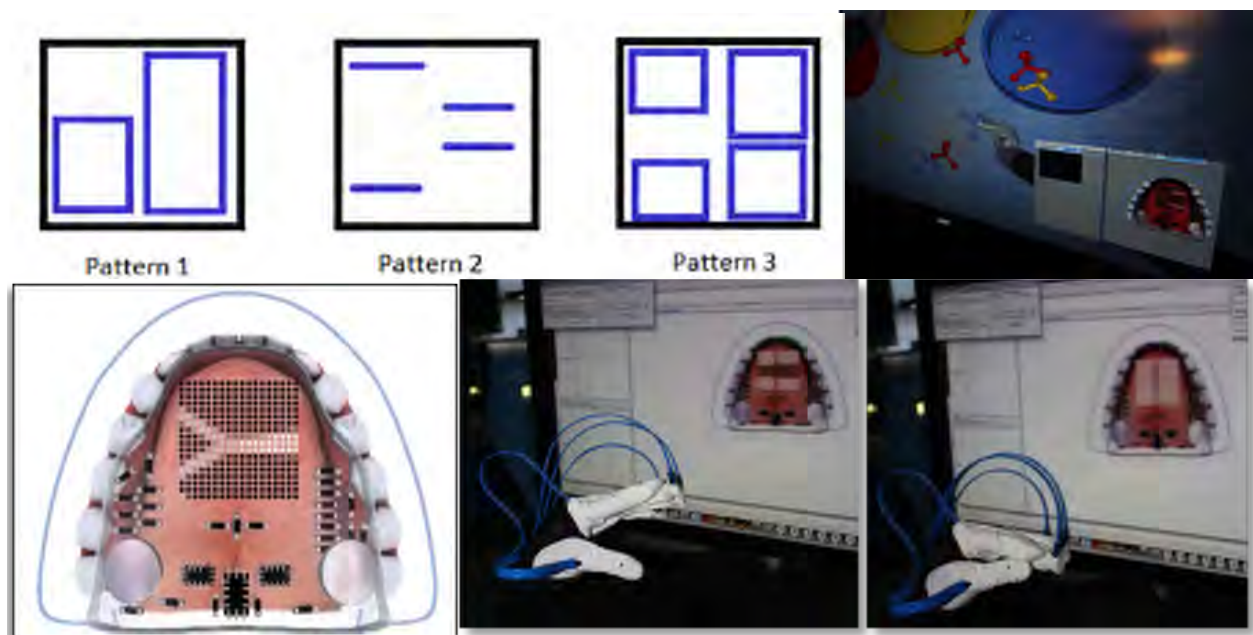
Figure 13-:(top row) Three different symbologies for representing grasper closure angle on the tongue. (bottom row) Two approaches for end effector electrotactile representation. (bottom row left) One open and one closed grasper (right grasper is closed firmly resulting in higher stimulus intensity). (bottom row right) An alternate representation (Pattern 3 from top row) of the tactile symbology.

The BrainPortAgent includes a graphical user interface (GUI) that provides visual feedback to the researcher regarding the tactile stimulus (Figure 13). The BrainPortAgent converts the image into a grayscale intensity map delivered to the BrainPort® Intraoral tongue array (Figure 13 bottom row). The tactile iconography includes: 1) Soft- the intensity first increases slowly when the grasper encounters an object and then more rapidly as the grasper closes (similar to the force sensation when we squeeze a soft object); 2) Medium- the intensity remains directly proportional to the distance between the fingers (using a variable gain set before use); 3) Hard- intensity sharply increases as soon as the grasper contacts an object and 4) Isointensity- only grasper closure angle is represented, with intensity held constant.

Figure 14: (left) Graphical representation of VideoTact display of the robot arm positions relative to endoscope orientation. The tactile wedges represent the projection of the robot arm shafts outside the field of view of the camera back to the entry port despite movement of the arms or camera (center). In addition, increased force on the shafts (e.g., from contact with ribs) causes increased intensity of the signal (right). This allows the user to maintain awareness of arm positions, movements and forces that remain outside the visual display of the camera field of view (black rectangle at the center).

To improve perception of the locations of the robot arms beyond the field of view of the surgeon, we added symbology to with the VideoTact to present the relative positions of the end effector shafts in screen coordinates (Figure 14). Stimulation frequencies of 1Hz, 4Hz and 10Hz represented each arm when projected onto the user's abdomen. As was predicted, 10Hz greatly facilitated recognition. While initial evaluation indicated that three moving arms were more difficult to differentiate effectively than just one or two arms, further symbology development improved the saliency of all three robot arm icons.
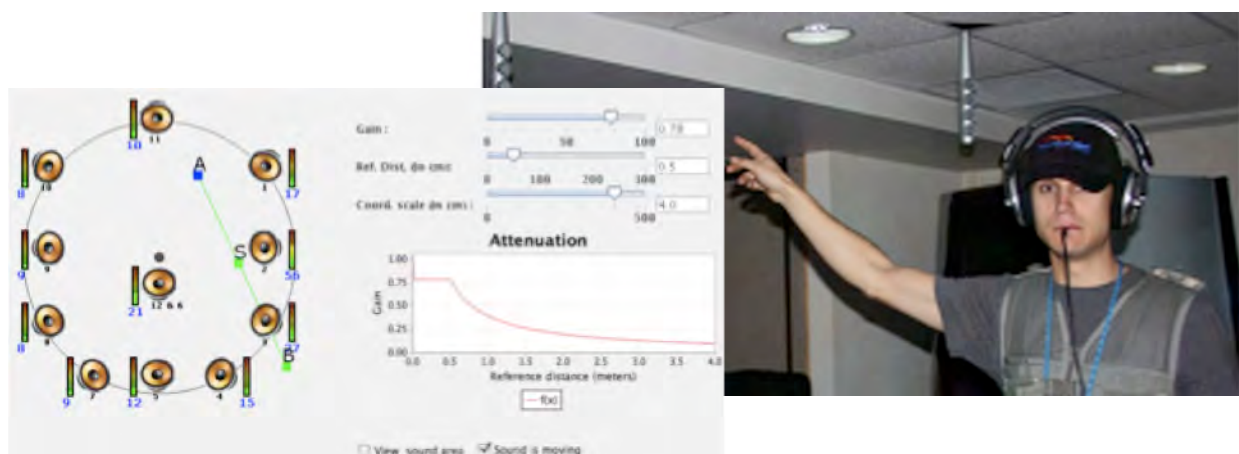
Figure 15: Surround Sound (10.2 channel) AMI agent GUI for spatially positioned audio stimuli.

Auditory Feedback: The AMI framework also allows the final software element to transform any of the tactile cues into spatial auditory cues (Figure 15). In the above example, the agent manipulates range and bearing to represent the grasper closure angle and force in surround

sound using fore/aft sound position and up/down tone frequency, respectively. The agent can play multiple sounds, both complex and simple to represent data (e.g., forces, locations, etc.) in the operative field. While mapping forces onto the tongue gave the user a finer degree of control during manipulation of the objects with the graspers, the audio display enabled users to easily manipulate two objects with different compliance and mass simultaneously.

The agent receives data from the Mimic Simulation Agent, Collision Manager Agent, or other AMI agents and applies appropriate attenuation to a sound signal to present azimuth and range on an oval array of 10 speakers and two subwoofers (Avia PowerStixx, FuShan Enterprises, Fremont, CA) mounted in the ceiling driven by a 12 channel digital audio interface (AudioFire12, Echo Digital Audio Corp., Santa Barbara, CA). The dimensional audio also proved effective for use as a spatial warning system in a collision manager feature implemented in ACMI-SATS (described below). Though designed for representation on the TTI, AMI allows for evaluation of collision manager functions implemented in surround sound.

Modality	Device	Characterization of the feedback	Relation to human Machine interaction design
Tactile	BrainPort® (Tongue)	Electrical stimulation: • 400-700+ electrodes • Different levels of intensity and stimulation wave form (e.g., Tactile "color" or "tone") • Patterns of stimulation can generate shapes, movement, tactile illusions	Force and position feedback for grasping
Tactile	VideoTact (Abdomen)		Relative positions of the arms outside of the field of view
Tactile	Tactile Torso Interface (TTI) (Upper Body)	Vibro-tactile stimulation: • 24-48 tactors • 3D array can provide range, azimuth and elevation • Effective for SA of movements of the arms out of the field of view •Offering a good sustained attention	Orientation of all arms in 3D space, movement of the arms, location of collisions (alarms), feedback for mode validation (e.g. switch in arm control)
Auditory	Spatialized (Surround) Sound System	Meaningful auditory cues: • Voices • Alarms • Distance and relative bearing • Different intensities and frequencies (to simulate intensity, range, etc.)	Localized warnings (collisions, limits of arm motion…) and feedback for validation, errors, etc.
Visual	Large screen Display	Kinesthetic mapping to visual movements Pseudo-3D using head tracking to provide parallax	Enable fine control (sewing) Head tracking allows freedom of movement Dynamic switching of surgical station or active user

Figure 16: Multisensory modality capabilities and potential uses in telesurgical data display.

We can now utilize audio, tactile and visual cues to reduce the effort required to complete a simulated surgical task. By placing feedback related to forces in the operative field on tactile and auditory interfaces, we can provide veridical sensory information without the haptic force feedback approach that interferes or competes with fine motor control. The flexibility of AMI

enables efficient design of research protocols that will seek to determine the best set of multi-sensory displays and symbology strategies for specific tele-surgery applications (Figure 16).

Teamwork

The reduction in workload associated with more intuitive multisensory interfacing should allow increases in productivity, such that a single surgeon could manage more than one case at a time, in concert with assistants or other specialty surgeons. This would be of particular use in mass casualty/battlefield events where multiple patients in multiple facilities, would require interventions from multiple surgical specialties who may be physically in different locations. For example, a vascular surgeon could repair a superior mesenteric arterial injury in one patient and then switch immediately to a previously prepped patient in need of a right renal artery repair or ligation (and then switch back quickly, if needed). When the vascular surgeon releases control of the second robot, the urologist takes over to repair a severed ureter or initiate a nephrectomy.

Because we have abstracted the control interface from the robot, any number of surgeons could interface individually to either control robots located in different facilities or interact on the same case. In the latter case, a surgeon and a first assistant could share control of the multiple robot actuators on the same case to improve efficiency, teaching and telementoring. ACMI-SATS utilizes gesture-based switching between simultaneous procedures or between members of a surgical team. To initiate a change, the surgeon makes a clutch gesture (quickly makes a fist with both hands) to lock the current procedure robot. He or she then turns to face the video monitor for the other case and again makes the clutch gesture to release its robot and proceed with the case. ACMI-SATS uses the AMI head-tracking agent to determine which procedure will receive each user's commands. It also switches the inputs to the multisensory displays so that the surgeon receives tactile and auditory feedback referenced to the currently active case only. To support multiple users during collaborative robotic procedures, the surgeon can release one or more robot arms to the first assistant and quickly take back control if needed (Figure 17).

Figure 17: ACMI-SATS implementation with Mimic dV-Trainer showing single surgeon management of two simultaneous cases. The end effectors and camera view move with the user in one case at a time, selected by intuitive user gestures. Tactile interfaces (lower center) provide sensory augmentation for the currently active case by providing position and force information to the user.

Alternatively, multiple surgeons can operate the same robot (or perhaps two separate robots) on the same patient at the same time (Figure 18). In the scenario developed by IHMC, an expert specialty surgeon (e.g., cardiovascular) mentors a fellow. The expert, perhaps located in his or her office, takes control after the local surgeon preps the robot and patient. The expert orients the end effectors and retractors, reviews the procedure with the fellow or first assistant and then clutches his or her controls (i.e., the Mimic dV-Trainer control console). At this point the fellow can unclutch, assume command of the robot and begin the technical portion of the case. To prevent inadvertent motion of the robot at transfer, the trainee must orient his or her hands to match the orientation of the dV-Trainer EndoWrists® and grasper closure angles (as visible on the video screen) before ACMI-SATS allows the end effectors to move. As desired, the mentor can unclutch, match wrist orientation and grasper angles, and take over control. Either can manipulate the third robot arm at any times in order to adjust retraction or to cut sutures. This enables effective telementoring and interactive telesurgical training and collaboration.
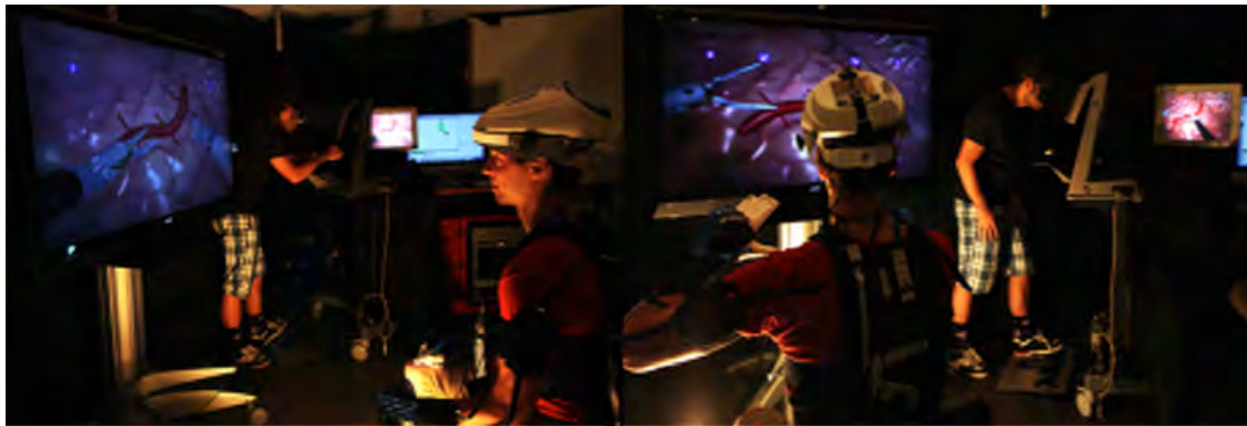
Figure 18: Collaborative control of a single procedure with ACMI-SATS. (left) The surgeon (plaid) sets up the procedure (using the mechanical control console interface) for the first assistant (red shirt). (right) The surgeon clutches his controls and the first assistant performs the procedure using the ACMI-SATS system. The surgeon monitors and can take over if needed, at any time. The two collaborators could control the robot from facilities and neither is required to be collocated with the patient.

Gesture based control

In addition to direct EndoWrist®, grasper and camera position/orientation mapping from the ShapeWrapIII and OptiTrak motion capture systems, ACMI-SATS uses specific gestures to manage functions normally controlled by foot pedals, such as clutching and electrocautery, as well as a number of functions not available on a surgical robot such as group positioning, "follow my example" and "no-fly zone" definitions for collision avoidance.

Clutching: Rather than rely on a foot pedal actuation to clutch and unclutch the robot, ACMI-SATS uses a fist clench gesture to engage the clutch. Clenching the right hand activates the clutching mechanism for the arms while clenching the left hand clutches the camera. Rotation of a clenched fist locks that part of the robot (akin to turning a deadbolt). This allows the surgeon to lock the camera movement, for example, so that it does not slave to his or her head movement. The surgeon then continues the procedure by unclenching both fists. Locking the actuators would allow a surgeon to, for example, review an MRI scan on a radiology display terminal and then return to complete the procedure.

No Fly Zone: Surgical mishaps have occurred due to poor surgeon SA. While the improved sensory feedback provided by ACMI-SATS should mitigate loss of SA, an additional gesture based feature allows the surgeon to designate "no fly zones" within the body cavity and receive warnings when the actuators encroach on volumes that have been identified by the surgeon as

areas to avoid. The surgeon positions the tip of robot arm 1 and defines a no fly zone by touching the right thumb and the right little finger after. Opening the fingertips places a default size no-fly zone at that location in the operative field. The surgeon can define larger zones with the same gesture by moving arm 1 before releasing the gesture. This defines the diameter of a spherical volume exclusion zone. Using the same thumb/little finger gesture, multiple no fly zones can be defined using the right hand and deleted, with the left hand, while touching near a zone with robot arm 2. We created a GUI (figure 19) to ensure accurate monitoring of the process during testing, however, this display would be distracting to the surgeon and the primary use is to maintain SA of areas outside the endoscope field of view. Therefore, when an instrument approaches or enters a no fly zone, the AMI agent represents the information either with spatialized audio using the surround sound array or on tactually on the TTI. AMI automatically assigns specific sounds or vibration frequencies to each zone. Should any part of the robot end effectors start approaching too closely, the assigned sound or vibration intensity increases along the bearing to the zone, relative to the endoscope field of view.
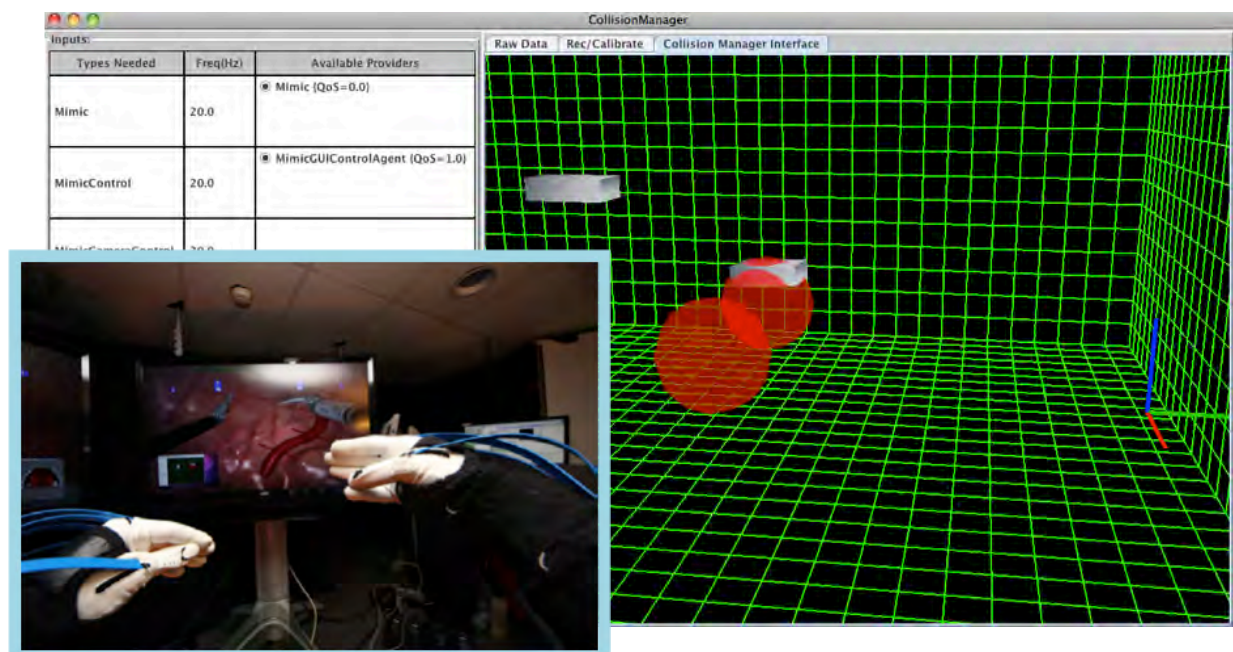
Figure 19: No fly zone defined or deleted with gestures (inset) appear on the test operator GUI for test and evaluation. Escalating spatially relevant tactile or audio warnings indicate no fly zone violations.

"Follow My Example": Repetitive tasks become burdensome in robotic surgery in comparison to open procedures. In open procedures, for example, surgeons can rapidly place a line of interrupted sutures with even spacing and tension, but they must slow their pace during robotic procedures due to the lack of qualitative feedback about the tissue friability and suture tension. ACMI-SATS incorporates a "follow me" function that allows the surgeon to define a macro of actions and then instruct the robot to execute a series of these actions, adding a position offset between each until the series is completed. IHMC demonstrated this function in the "pick and place" practice drill available in the Mimic dV-Trainer software (Figure 20), using an iterative task similar to placing surgical staples along an incision line. While the current ACMI-SATS implementation only repeats position commands, including adding offsets between iterations, it could be extended to track the forces on the graspers and actuator arms. With force measurements and position control, the software agent could maintain constant force or indicate an error if force parameters are exceeded (e.g., when a suture needle strikes an arterial plaque during an anastomoses). We will also implement gestural control methods to bypass the GUI when defining macros in future research activities.
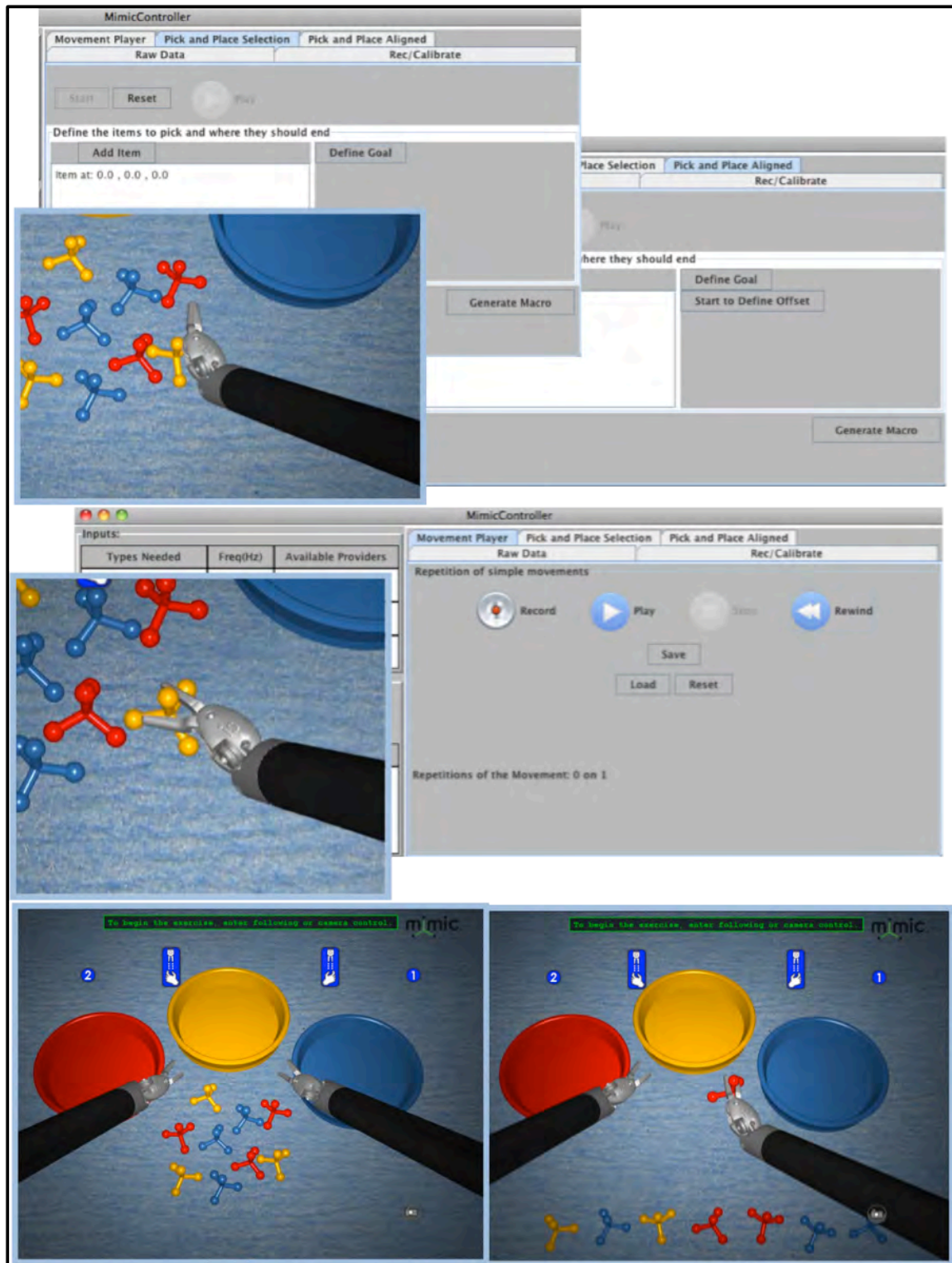
Figure 20: Follow my example macro for repetitive task (i.e., align randomly placed objects. Step 1 (top), mark position of all jacks (inset) by touching the grasper to each one. Step 2, mark goal by touching a destination and, if desired, a second point to define an offset. In step 1 & 2, the agent stores the X, Y, Z positions of the jacks and the goal from the 3D position of the grasper. Step three (bottom) a previously defined jack grasping macro (middle) is nested in the alignment macro and the system iteratively picks up and places each jack (bottom, left) in a line with the spacing defined in step 2 (bottom, right).

Group positioning: The group positioning feature allows for rapid, gross position control of all three arms simultaneously. This feature finds use when moving to a different location within the operative field (as might happen when a vascular surgeon hands off control to a urological surgeon). The surgeon first clutches both the camera and the actuators as described above. He or she then extends the index finger, middle finger and thumb on the right hand while keeping the left hand clenched (Figure 21). At this point the EndoWrists® track the relative position and orientation of the three extended digits and allow the surgeon to move them into a favorable starting position. Re-clutching and unclutching both hands returns to normal motion tracking behavior for fine position control and continuation of the procedure. This method could be easily applied to control robots with four or five active actuators (in addition to an endoscope).

Figure 21: Group positioning gesture with left hand clenched and first three digits of the right hand extended to position the three arms simultaneously.

Energy: Rather than require foot pedals for activation and selection of energy dissection and cauterization, ACMI-SATS utilizes a clutch followed by extending index and middle finger together (thumb and other two fingers clenched) gesture to select and activate energy dissection. The closed grasper moves with the fingertip position to dissect electrosurgically. Cauterization control operates in a similar fashion, however, both the index finger and thumb must be extended to select electrocautery, and touching the fingertip to the thumb closes the grasper and activates the energy.

Relationship to award Statement of Work

We developed a multisensory interface that provides visual, audio and tactile displays as well as incorporates veridical kinesthetic and proprioceptive cueing. In addition, we have created a generalizable, intuitive control interface for surgical robots using motion capture and gesture detection to command the robotic system. Based on the original statement of work, we have completed all of the tasks from Specific Aims # 1 and 2 which included:

Specific Aim # 1: Develop a multi-sensory interface to augment current visual and haptic interfaces that will include of spatial audio and tactile interfaces
Task 1. Modify IHMC Auditory and Tactile interfaces for telesurgical application
　　1a. Select tactile displays and body mounting locations
　　1b. Define intracorporeal orienting requirements
　　1c. Define registration method for marking locations of organs and vessels
　　1d. Evaluate tactile and audio cueing representations

    1e. Integrate software for spatial cueing
       Milestone #1: Spatial audio and tactile interface critical design review
Task 2. Integrate IHMC AMI software & Mimic dV-Trainer-Mantis Duo
    2a. Define interface over Ethernet
    2b. Test transmission of dV-Trainer state variables over Ethernet to AMI
    2c. Test transmission of AMI control input data variables to dV-Trainer
    2d. Develop hardware interface to existing telesurgical robotic end effectors
    2e. Develop software interface to existing telesurgical robotic end effectors
       Milestone #2: Complete software Ethernet interface definition and testing

Specific Aim #2: Develop a generic telesurgical robot control input mechanism that allows use of normal kinesthetic hand and arm movements using motion capture and gesture recognition
Task 3. Code software for natural movement control of ACMI-SATS
    3a. Define and integrate motion primitives for telesurgical activities
    3b. Bind coded motion primitives to dV-Trainer control input commands
    3c. Code user interface
    3d. Code performance evaluation interface
    3e. Test and evaluate interface function with tactile and audio displays
    3f. Code finite state machine (FSM) algorithm for gesture recognition
    3g. Test and evaluate gesture based commands in dV-trainer simulation
       Milestone #3: ACMI-SATS system design complete
Task 4. Demonstration and evaluation
    4a. Prototype system functional verification and testing
    4b. Demonstration and evaluation with subject matter expert Co-Investigator
    4c. Analyze results for presentation at the Society of American Gastrointestinal and Endoscopic Surgeons (SAGES) annual conference
       Milestone #4: Demonstrate ACMI-SATS system with simultaneous simulated procedures
       Milestone #5: Draft manuscript for submission to Surgical Endoscopy (journal)

Key research accomplishments

- We successfully integrated our AMI software architecture with a physical four arm surgical robot (Zeus) and with a commercially available tele-surgical simulation (dV-Trainer)
- We created a physics-based kinematically accurate graphical simulation of the Zeus robot
- We integrated spatial audio, tactile and large format visual displays for improved surgeon situation awareness.
- We have evaluated a number of electrotactile and auditory symbologies for representation of the positions and forces on the end effectors as well as relative locations and forces on the robot arm shafts.
- We have integrated a wireless full-body, wearable motion capture system (ShapeWrapIII) and head tracking (OptiTrack) to allow full freedom of movement for the surgeon.
- We implemented gesture based control elements into the ACMI-SATS testbed to provide intuitive mode switching and tele-robotic system control
- We implemented a 1:1 scaling between arm and hand movements and the visual representation of the endoscopic view to ensure useful kinesthetic, proprioceptive and motion parallax cues.

Reportable outcomes

We presented our preliminary approach and results at the Aerospace Medical Association's 81st Annual Scientific meeting two posters (general section and Emerging Technologies section) describing the ACMI-SATS system to the Society of American Gastrointestinal and Endoscopic Surgeons annual scientific session (SAGES 11).

Raj, A. K. & Cameron, J. D. (2010).Multisensory Augmentation of Telemedicine Systems,*Aerospace Medical Association 81st Annual Scientific Meeting*, Phoenix, AZ.

Raj, A. K**.,** Moucheboeuf, A., Holmgren, A., Hutcheson, T. L., Cameron, J. D., Lecoutre, D. V. & Vassiliades, T. A. (2011) An anthro-centric multisensory interface for sensory augmentation of tele-surgery. Proceedings of the Society of American Gastrointestinal and Endoscopic Surgeons Annual Scientific Session (SAGES 2011), San Antonio, TX. Abstract # 33996.

Raj, A. K**.,** Moucheboeuf, A., Holmgren, A., Hutcheson, T. L., Cameron, J. D., Lecoutre, D. V. & Vassiliades, T. A. (2011) An anthro-centric multisensory interface for sensory augmentation of tele-surgery. Proceedings of the Society of American Gastrointestinal and Endoscopic Surgeons Annual Scientific Session (SAGES 2011), San Antonio, TX. Emerging Technologies Abstract # 36243.

A journal paper has been drafted and will be submitted to Surgical Endoscopy.

Conclusion

The ACMI-SATS project developed a testbed that allows for testing and evaluation of hypotheses related to tele-surgical robotic human-centered surgeon interfaces, cognitive workload, efficiency and situation awareness. The ACMI-SATS testbed includes both physical surgical robotic capability (Zeus) and simulation environments (Zeus/Yobotics, da Vinci®/Mimic) to maximize the efficiency of system development. We have completed the testbed hardware and software, and our research staff has completed functional verification of ACMI-SATS augmentations. Force feedback systems that backdrive against the user's hands can cause the surgeon to increase force against the hand controllers and lead to rapid velocity changes when the position controlled actuators interact with tissues with variable compliance. ACMI-SATS avoids this issue by providing veridical sensory feedback without interfering with fine motor control movements of the hands. The completed ACMI-SATS testbed will support future studies to develop optimal tele-surgical, tele-mentoring and remote operations technologies and methodologies for both military and civilian applications.

Future work would include extending the SLAM 3D models to maintain a wider field of view in the model as the camera is moved, reducing the size of the depth sensor (e.g., Aerius Photonics, LLC, makes a number of small rangefinders that could be integrated into endoscopes), and testing performance gains in standard surgical procedures (as well as those enabled only by the capabilities of ACMI-SATS). Because the ShapeWrapIII system used in this prototype was designed primarily for capturing movement for animation and gaming, it is more obtrusive than desirable for an operational ACMI-SATS system. More compact motion sensing systems could eventually remove the requirement for body worn technologies altogether. While this team and others (Dunn 2011) developed solutions for sensing and modeling the operative field using commercial off the shelf (COTS) sensors such as the Microsoft Kinect™, we determined that this device is not adequate for surgeon motion capture. It lacks the resolution to track the orientations and positions of the individual fingers, and the relatively low sample rate prevents effective real-time signal processing, which would be needed for repeatability and accurate registration. Future robotic end effectors that replace the position controlled mechanical drives in the actuators with force controlled drives would allow for better control of the end effectors when working with tissues with variable compliance. This would enable a more functional force following capability for the "follow my example" function of ACMI-SATS and prevent mishaps, such as inadvertent tissue injury, that manifest with position control.

The military clearly would benefit from improved telemedical systems that allow more rapid delivery of definitive medical care to wounded warfighters. ACMI-SATS could complement DoD projects such as the DARPA Trauma Pod that will reduce the time between battlefield injury and

definitive treatment by providing a method for a surgeon geographically removed from the soldier to rapidly intervene, without having to wait for transportation to a field hospital, stabilization and airlift to a level I trauma center. The civilian world of medicine could also benefit tremendously from telesurgical systems enabled by ACMI-SATS. The ability to perform surgery from a distance will prove extremely useful in places and situations where distance, disaster, lack of infrastructure, or the prohibitions of cost may preclude the presence of expert surgeons. Removing the need for a medical expert's actual presence in these situations creates opportunities to provide essential medical care to persons who might otherwise not receive it.

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Appendices
Appendix 1: Abstracts

Raj, A. K. & Cameron, J. D. (2010).Multisensory Augmentation of Telemedicine Systems,*Aerospace Medical Association 81st Annual Scientific Meeting*, Phoenix, AZ.

Introduction: Modern electronics, software and networking technologies have enabled the development of telemedicine capabilities that bring medical expertise to remote locations. Additionally, telemedicine enables telementoring to allow more individuals to benefit from interactions with expert practitioners. The aerospace medical community has embraced these novel concepts, which have the potential to dramatically improve delivery of care to deployed units or vehicles in flight. The available interfaces, however, provide primarily visual information with some additional verbal auditory data. This prevents the physician from experiencing the rich multisensory cues utilized in normal one-on-one patient or training interactions. Previously we have developed an anthro-centric multisensory interface (ACMI) system that can manage multiple types of data streams and display information to users via visual, audio and tactile.

Methods: The adaptive multiagent integration (AMI) software agent architecture was used to integrate video imagery, surround sound audio and tactile representations of information during telemedical simulations. This ACMI implementation provides typical video feeds with adjustable levels of visual graphic overlay. Multiple microphones capture spatial relationships of the auditory environment (represented using surround sound). Combined with tactile spatial orientations interfaces that provide perception of items outside the visual field provided by the camera, these displays improve user situation awareness (SA).

Results: Performance (time to complete, number of errors) improved for individuals when using telemedicine apparatus with ACMI vs. no ACMI enabled for a series of telemedicine relevant simulated tasks.

Discussion: Telemedicine holds great promise for use in aerospace environments. Augmentation with multisensory displays could enhance effectively and expand capabilities and applications without increasing user workload.

Learning Objective 1
Current methods for multisensory interface implementations will be described.

Learning Objective 2
Techniques for improving multisensory situation awareness without increasing system bandwidth usage will be discussed.

Learning Objective 3
Effectiveness of multisensory interface in telemedicine applications will be discussed.

Raj, A. K., Moucheboeuf, A., Holmgren, A., Hutcheson, T. L., Cameron, J. D., Lecoutre, D. V. & Vassiliades, T. A. (2011) An anthro-centric multisensory interface for sensory augmentation of tele-surgery. Proceedings of the Society of American Gastrointestinal and Endoscopic Surgeons Annual Scientific Session (SAGES 2011), San Antonio, TX. Abstract # 33996.

Raj, A. K., Moucheboeuf, A., Holmgren, A., Hutcheson, T. L., Cameron, J. D., Lecoutre, D. V. & Vassiliades, T. A. (2011) An anthro-centric multisensory interface for sensory augmentation of tele-surgery. Proceedings of the Society of American Gastrointestinal and Endoscopic Surgeons Annual Scientific Session (SAGES 2011), San Antonio, TX. Emerging Technologies Abstract # 36243.

Appendix 2: Acronyms

3D – Three Dimensional

ACMI-SATS - Anthro-Centric Multisensory Interface for Sensory Augmentation of Tele-Surgery

ADC – Analog to Digital Converter

AMI - Adaptive Multiagent Integration

BMI - Brain-Machine Interface

BORIS - Basic Operational Robotics Instruction System

DAC – Digital to Analog Converter

DARPA - Defense Advanced Research Projects Agency

DoD - Department of Defense

ERF - Electro-rheological fluid

fMRI - Functional Magnetic Resonance Imaging

FSM - Finite State Machine

GUI- Graphical User Interface

HAPsMRT - High Altitude Platforms Mobile Robotic Tele-surgery

HD - High Definition

HMD – Head Mounted Display

HMI- Human Machine Interface

IED - Improvised Explosive Device

IHMC – Institute for Human and Machine Cognition

MRI – Magnetic Resonance Imaging

NASA - National Aeronautics Space Administration

SA - Situation Awareness

SAGES - Society of American Gastrointestinal and Endoscopic Surgeons

SLAM – Simultaneous Localization and Mapping

SCS – Simulation Construction Set

TTI – Tactile Torso Interface

TATRC - U. S. Army Telemedicine and Advanced Technology Research Center

TSAS - Tactile Situation Awareness System

UAV – Unmanned Aerial Vehicle

VE - Virtual Environment

VR - Virtual Reality